J. Hydrol. Hydromech., 72, 2024, 4, 422–435
https://doi.org/10.2478/johh-2024-0028

sciendo Journal of Hydrology and Hydromechanics Institute of Hydrology SAS

Comparing the effects of hydromulching and application of biodegradable plastics on surface runoff and soil erosion in deforested and burned lands

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Abstract: Several techniques, such as hydromulching (HM) and addition of organic residues (such as biodegradable plastics, BP) to soil have been proposed for conservation of soil affected by deforestation and wildfire. However, there is the need to support the task of land managers for the adoption of the most effective soil conservation technique, considering that the impacts on soil properties and hydrology are different due to the different mechanisms (mainly based on root actions for hydromulching and on supply of organic matter for application of bioplastics residues). This study comparatively evaluates the hydrological and erosive effects of HM, addition of BP residues to soil, and lack of any treatments (control) at the plot scale and under simulated rainfall in deforested and burned forestlands of Northern Iran. These effects have been associated to changes in key properties of soil and root characteristics due to the treatments, using multivariate statistical analysis. Moreover, regression models have been setup to predict surface runoff and soil erosion for both treatments. HM was more effective (–65% of runoff and –61% in soil loss) than application of BP (–22% and –19%, respectively) in controlling the soil's hydrological and erosive response, the latter being extremely high in control plots (over 6 tons/ha). These reductions were closely associated to significant increases in organic matter and aggregate stability of soil, to a decrease in bulk density after the treatments, and to the grass root growth, which further improved soil hydrology after HM. The Principal Component Analysis provided a synthetic parameter measuring the soil response to rainfall and treatments. The cluster analysis discriminated the three soil conditions (HM, application of BP and control), according to the changes in soil properties and root growth in HM, in as many groups of soil samples. The multiple regression analysis provided two linear models that predict surface runoff and soil loss with a very high accuracy ($r^2 > 0.98$) for a precipitation with given depth and intensity.

Keywords: Surface runoff; Soil loss; organic matter; Aggregate stability; Bulk density; Multiple regression; Prediction models.

1 INTRODUCTION

Erosion is one of the most severe soil degradation agents on a global scale (Zhao et al., 2019), especially in delicate ecosystems, such as the undisturbed forestlands. In these environments, heavy deforestation and severe wildfires reduce biodiversity and ecosystem functions (Decaëns et al., 2018; Lucas-Borja and Delgado-Baquerizo, 2019). Increases in surface runoff and soil erosion (Cherubin et al. 2017; Parhizkar et al. 2020a; 2020b), due to removal or burning of the vegetal cover of forests as well as to changes in soil properties (Shabanpour et al., 2020), are other severe impacts of deforestation and wildfires. Water and sediment fluxes originated in forestlands after these disturbances often extend in valley environments with flooding and infrastructure burial due to erosion (Bradshaw et al., 2007). There is, therefore, the need to control and mitigate the severe impacts of deforestation and fire in areas that are prone to the hydrological hazards (Sarvade et al., 2019).

In recent decades, several nature-based solutions for soil conservation have been proposed and experimented worldwide (Busari et al., 2015; Dumanski, 2015). Soil mulching and addition of organic residues (such as biodegradable plastics) have been found as cheap and sustainable practices to limit surface runoff and erosion rates in agro-forest areas (Meena et al., 2019; Prosdocimi et al., 2016). Soil mulching, which consists of a protective layer (mulch) of organic (e.g., crop residues) or inorganic (e.g., gravel, bioplastic elements) materials (Patil Shirish et al., 2013; Prats et al., 2017), reduces the rainsplash erosion and overland flow velocity as well as increases soil infiltration and water storage (Prosdocimi et al., 2016). Hydromulching (hereafter indicated as "HM") has been proposed to increase the effectiveness of mulching thanks to the action of living vegetation against runoff and erosion (McCullough and Endress, 2012), especially where the vegetal cover is scarce. HM consists of spraying a slurry of seed, water, fertilizer, binding agents, super-absorbents, fiber mulch and green dye on soil surface (Bautista et al., 2009; Dodson and Peterson, 2009; Parsakhoo et al., 2018a). After HM, grass covers the soil surface, which increases water infiltration, interception and evapo-transpiration, and reduces overland flow and rainsplash erosion (Li et al., 2011). The main beneficial effect of grass in hydromulched soils is played by roots, which bind the soil particles and increase its aggregate stability, reducing the soil detachment capacity and therefore the soil loss (Parhizkar et al., 2021a; Wang et al., 2018a; 2018b). Gillespie et al. (2020), Miralles et al. (2009) and Zhang et al. (2008) stated that herbaceous species support improvements in both soil hydrology and quality.

Application of biodegradable plastics (BP) to soil increases its organic matter content (Steinmetz et al., 2016; Zhang et al., 2020), which is considered as one of the most common indicators of good soil quality (Pathak et al., 2005). This increase improves several physical, chemical, and biological properties (Abiven et al., 2009; Luna et al., 2018), especially soil aggregate stability and bulk density of soil. The latter properties have been recognised as key drivers of the hydrological response of soil after treatments for soil conservation Therefore, this practice maximizes the positive effects of organic matter on soil's resistance to degradation agents, such as erosion. Beside soil conservation, the anti-erosive treatment based on application of bioplastic residues reduces the cost of treatment or disposal in landfills (Yadav et al., 2020).

Thanks to these beneficial effects on soil hydrology, both HM and application of BP are potentially viable soil conservation techniques to reduce runoff generation and soil erodibility in deforested and severely burned forests. The effects of HM and BP addition to soil have been studied in several environments. Regarding HM, reductions in soil erosion by 50% to 85% have been found in quarries (Eck et al., 2010) and furrow irrigation (McLaughlin and Brown, 2006) in North America as well as in artificial soil slopes of forest roads (Parsakhoo et al., 2018a) or in deforested hillslopes (Parhizkar et al., 2021c) in Iran. Compared to HM, much less research exists on the anti-erosive effects of BP application. In general, the literature reports beneficial effects of distribution of BP on bulk density, aggregate stability, and porosity of soil (Angelova et al., 2013; Siczek and Frac, 2012), and these effects result in decreased runoff generation and soil erodibility (Meena et al., 2020; Prosdocimi et al., 2016). For instance, according to Jiang et al. (2020), the application of BP to agro-forest sites can reduce particle detachment from soil, due to raindrop impact and overland flow.

However, the effects of mulching and organics addition on soil are site-specific (Bombino et al., 2019; Prosdocimi et al., 2016), depending on the characteristics of the treated soils as well as on the rates and times of application (e.g., Parhizkar et al., 2021b). Therefore, the effectiveness of these conservation practices must be properly investigated, before deciding the treatment of a given site with HM and BP. Moreover, no previous studies have compared the effectiveness of these techniques to reduce surface runoff and soil loss in deforested or burned lands. This comparison may indicate to land managers which of the two soil conservation techniques as well as their main anti-erosive actions (mainly based on the improvement in the physico-chemical properties of soil for BP, and on the contribution of grass roots to reduce soil particle detachment for HM) is more feasible at reducing surface runoff and soil loss in areas affected by intense deforestation.

The general objective of this study is the comparative evaluation of the hydrological and erosive effects of HM and addition of BP to soil at the plot scale and under simulated rainfall in deforested and burned forestlands of Northern Iran. The specific objectives are the following: (i) estimating surface runoff and soil loss after the treatments in comparison to untreated soils (control); (ii) associating the effects of the treatments on soil hydrology to changes in key properties of soil and root characteristics; (iii) evaluating the overall impacts of HM and BP treatments on soils through multivariate statistical analysis; and (iv) propose regression models to predict surface runoff and soil erosion for both treatments.

The results of the study should indicate to hydrological engineers and landscape managers the most effective soil conservation technique to limit surface runoff and soil erosion in deforested and burned forestlands of the semi-arid environment.

2 MATERIALS AND METHODS

2.1 Description of the study area

The study area is Khortum forestland (coordinates 37°07′115″ N; 49°29′35″ E), located in Jirdeh, Shaft County, 17 km south of Rasht city (Guilan province, Northern Iran). The area has an elevation of 60-70 m above the mean sea level. Its climate is Mediterranean, Csa type (Köppen's classification, Kottek et al., 2006). The mean annual temperature and rainfall are 16.3 °C and 1360 mm (mostly distributed from October to December), respectively (data of the last 20 years reported by the Iranian Meteorological Agency).

The soil is Cutanic Luvisols (Clayic) (according to WRB) and Ultic Hapludalfs (USDA Soil Taxonomy). Its texture is silty clay loamy (Nachtergaele, 2001; Soil Survey Staff, 2014) with 12.9% of sand, 47.8% of silt and 39.3% of clay, whereas the prevalent soil slope is on average 15%. Table 1 reports the mean values of the main chemical properties of soil as its preliminary characterization.

Table 1. Mean values of the main chemical properties of soil as its preliminary characterization.

Soil properties	Value
pH (–)	7.12
Organic carbon (%)	1.83
Total nitrogen (%)	0.15
Phosphorus (mg/kg)	10.6
Cation exchange capacity (cmol/kg)	2.12
Limestone (%)	24.3

Some parts of these lands have been deforested, mainly due to the construction of civil works and severe fires. Signs of rill formation indicate intense erosion on several hillslopes after deforestation (Parhizkar and Cerdà, 2023).

2.2 Plot installation and soil preparation

Twenty-seven experimental plots were installed in the laboratory for rainfall simulations and hydrological measurements, and filled with soil collected in the study area. Each plot, made of wood, was 0.5-m wide and 1-m long with 0.1-m high sides. The base was made of wood (thus not impervious to water), and small holes were drilled to facilitate water drainage of the soil.

Soil was collected from the top layer (0 to 50 cm) of the deforested and burned area. Rocks, weeds, and litter were removed from the soil surface before collection, and then transported to the laboratory. Here, the soil was sieved (4-mm mesh) to remove gravel, the coarser fraction of sand (over 4 mm) and vegetation.

The collected soil was mixed and placed in the plots, whose upper surface was gently leveled by hand. A tarpaulin cover on the top avoided water evaporation until the rainfall simulations (Kukal and Sarkar, 2010). At the downstream side, each plot was equipped with a horizontal collector to convey water and sediment flows generated by the rain simulations through a PVC pipe into a plastic tank.

Three "soil conditions" were simulated in as many experimental plots: 1) deforested and burned soil without any treatments (hereafter indicated as "DU" and assumed as "control"); 2) deforested and burned soil, but treated with hydromulch (HM, Figure 2a); and 3) deforested and burned soil, treated with biodegradable plastic (BP, Figure 1b).

The DU, HM or BP soils showed the same characteristics (such as slope, type and texture), and experienced the same rainfall input and weather conditions across the experiments. Therefore, the effects of treatments can explain the changes in soil's hydrological and erosive response compared to the control plots.

2.2.1 Hydromulching

The substrate for soil hydromulching was a mixture of water, grass seed, organic binder, starter fertilizer, cellulose fiber, bio-humus, super absorbent, and green dye. These native materials were mixed according to the hydromulching international protocol (Albaladejo Montoro et al., 2000; Fox et al., 2010; Parsakhoo et al., 2018a; Sheldon and Bradshaw, 1997). Seeds of *Zoysia*, a grass locally growing in the warm season (Beiraghdar et al., 2014), were used, since its hard leaves and dense roots create a suitable vegetal cover for topsoil conservation (Figure 1a). Organic materials were added to the hydromulched soil, in order to bind soil particles into stable aggregates (Parsakhoo et al., 2018a; Sheldon and Bradshaw, 1997). Seed germination was supported by supplying cellulose fiber and bio-humus as absorbent materials (Babcock and McLaughlin, 2013; Dodson and Peterson, 2009; Holt et al., 2005). Finally, starter fertilizers and super absorbents were used to feed seedlings and increase the water holding capacity of soil, respectively (Abdallah, 2019; Parsakhoo et al., 2018b). Following the indications of previous studies (Holt et al., 2005; Ricks et al., 2020), the hydromulch was applied at a dose of approximately 40 g/m^2 (400 kg/ha) in 4 L water.

2.2.2 Biodegradable plastics

Containers of biodegradable plastic (BP, material based on corn starch and polylactide) were used. Polylactic acid is a biodegradable hydrolysable aliphatic semicrystalline polyester produced through the direct condensation reaction of its monomer, lactic acid, as the oligomer, and followed by a ring-opening polymerization of the cyclic lactide dimer. BP underwent a 9-month *in situ* incubation, in order to degrade the BP residues of the containers (Figure 1b).

Fig. 1. Pictures of plot treated with hydromulching (after grass growth) (a), residues of a biodegraded plastic container (after 9 months) (b) and rainfall simulator (c) used for the experiments.

2.3 Experimental design

The rainfall simulations under the three soil conditions (DU, HM and BP) were carried out at three dates (3, 6 and 9 months) after plot installation (from August 2022 to April 2023). Therefore, the experimental design consisted of three soil conditions (HM, BP and DU) × three dates (3, 6 and 9 months after soil preparation) × three replications, totaling 27 rainfall simulations.

2.4 Rainfall simulations

Runoff volume and soil loss were measured at each plot after a rainfall produced by a hand-crafted simulator installed 3.1 m above the laboratory floor (Figure 2c). This simulator consisted of two open rectangular boxes with a square grid (0.5 m × 1 m) as bottom. The grid was equipped with 70 syringes (diameter of 2.5 mm) with needles (outer diameter of 0.7 mm and length of 40 mm) to produce raindrops. Wind disturbance to the simulated rainfall was prevented by the laboratory walls. However, the plots were exposed to a moderate air stream to allow slight variations in the impact angle of raindrops.

The rainfall was simulated keeping constant its intensity throughout the experiment by a constant box refilling with tap water. The uniformity of the rainfall intensity (Duke and Perry, 2006) was 83%, which is an acceptable value according to the classification of "The Irrigation Association" (2002).

The rainfall intensity was set to about 100 mm/h (98 ± 1.1 mm/h after calibration). This is a very high value that simulates extreme rainfall events, occasionally occurring in this semi-arid forest and resulting in very high erosion rates. This intensity was calculated considering that, in some years, two to five rainfall events of one to two hours may account for half annual precipitation (1300–1400 mm, Modarres, 2006) in the area.

2.5 Measurement of runoff and soil loss

Before the rainfall simulation, the soil was saturated with tap water, slowly poured on the plot surface, until ponding. Then, the soil dried in the open air for 24 hours until to the field capacity.

After the simulation started, the volumes of water and sediments produced by the rainfall were collected. Each rainfall simulation was carried out for 30 minutes (Zhao et al., 2019). The surface runoff (SR) collected in the tank was measured after the rainfall simulation. Then, this volume was oven-dried at 80 °C for 24 h, and the dry sediment was weighted to estimate the soil loss (SL). The sediment concentration (SC) was calculated as the ratio between SL and SR. Finally, the time to runoff start (TRS) was measured after 9 months under the three soil conditions. TRS, which is the time when water starts to drop in the collecting tank, gives information about the rapidity of runoff generation.

2.6 Measurement of soil properties

The aggregate stability (AS), bulk density (BD) and organic matter (OM) of three small samples of soil randomly collected in each of the 27 plots were measured at the same dates as the rainfall simulations, using the wet-sieving (AS), oven-drying (BD) (Kemper and Rosenau, 1986) and Walkley-Black (OM) (Allison, 1975) methods.

Three samples of grass roots were also randomly collected from the plot treated with HM at the same dates. The length, biomass and weight density of roots were measured. The root length (RL) was determined, using a universal tape meter. The root biomass (RB) was measured on oven-dried (60 °C for 48 h) samples, after weighting for several times until a constant value. The root weight density (RWD) was measured by the washing method over a 1-mm sieve and subsequent oven-drying (at 65 °C for 24 h).

2.7 Statistical analysis

A two-way ANOVA (ANalysis Of VAriance) was used to identify the statistical significance of differences in the response hydrological variables (SR, SC, SL, and TRS) and soil properties (OM, BD, and AS) among the different soil conditions (DU, HM and BP), and survey times (3, 6 and 9 months) (explanatory variables). A one-way ANOVA (time as factor) was also applied to root characteristics in the HM plots as additional response variables. To satisfy the assumptions of the statistical tests, the hypotheses of normal distribution and homoscedasticity of data were checked using Shapiro-Wilk and Breusch-Pagan tests, respectively. The data were square root transformed when the first assumption was not met. Pairwise comparisons were carried out using Tukey's tests at $p < 0.05$.

Then, a Principal Component Analysis (PCA) was applied, in order to find correlations (using Pearson's coefficient, r) among the response hydrological variables and soils properties, and to identify the existence of meaningful derivative variables (Principal Components, PCs) (Rodgers & Nicewander, 1988) that may simulate the soil response to rainfall under the three soil conditions. The number of PCs explaining at least a percentage of 75% of the original variance was retained, since being the only PC with an eigenvalue > 1 (5.18).

Finally, the observations were grouped in clusters using Agglomerative Hierarchical Cluster Analysis (AHCA), a distribution-free ordination technique to group samples with similar characteristics from an original group of variables. As similarity-dissimilarity measure the Euclidean distance was used.

2.8 Modelling surface runoff and soil erosion

Multiple regression models between SR and SL (dependent variables), and the other measured (BD, OM and AS of soil) or categorical (soil condition and time) variables were setup to predict runoff and erosion under the three soil conditions over time from these input parameters. The prediction accuracy of these models was verified using the coefficient of determination (r^2) and the coefficient of efficiency of Nash and Sutcliffe (NSE, Nash and Sutcliffe, 1970), whose acceptance values (0.50 and 0.75, respectively) together with are the equations for their calculation are reported by Van Liew and Garbrecht (2003), Krause et al. (2005) and Moriasi et al. (2007).

3 RESULTS

3.1 Hydrological and erosive response of soil after HM and BP treatments

ANOVA revealed significant differences in all hydrological variables among the three soil conditions ($p < 0.0001$), but not over time ($p > 0.061$). The interactions between these two factors were significant for SR and SL ($p < 0.002$), and non-significant for SC ($p = 0.467$) (Table 2).

More specifically, the lowest SR (5.75 ± 0.63 mm) and SL (2.44 ± 0.05 tons/ha) were measured under HM after 9 months. The highest values were found for DU plots (20.2 ± 0.73 mm and 7.36 ± 0.07 tons/ha, respectively, both after 9 months). The BP

Table 2. Results of two-way ANOVA applied to the main soil properties and hydrological variables under the three soil conditions (BP = treatment with bioplastics; DU = deforested and untreated soil; HM = hydromulching) and at three dates (3 = three months; 6 = six months; 9 = nine months) in the study area (Khortum forest, Guilan province, Iran).

Factor	Degrees of freedom	Sum of squares	Mean squares	F	Pr > F
SR					
Soil condition	2	713.441	356.721	417.886	**< 0.0001**
Time	2	3.104	1.552	1.818	0.191
Soil condition × time	4	22.993	5.748	6.734	**0.002**
SC					
Soil condition	2	240.218	120.109	12.259	**0.000**
Time	2	10.517	5.259	0.537	0.594
Soil condition × time	4	36.548	9.137	0.933	0.467
SL					
Soil condition	2	80.662	40.331	3327.097	**< 0.0001**
Time	2	0.080	0.040	3.291	0.061
Soil condition × time	4	2.513	0.628	51.829	**< 0.0001**
OM					
Soil condition	2	8.432	4.216	2529.680	**< 0.0001**
Time	2	0.423	0.212	126.960	**< 0.0001**
Soil condition × time	4	0.261	0.065	39.090	**< 0.0001**
BD					
Soil condition	2	0.421	0.210	288.386	**< 0.0001**
Time	2	0.030	0.015	20.746	**< 0.0001**
Soil condition × time	4	0.005	0.001	1.840	0.165
AS					
Soil condition	2	1.291	0.645	2810.387	**< 0.0001**
Time	2	0.020	0.010	43.613	**< 0.0001**
Soil condition × time	4	0.018	0.004	19.177	**< 0.0001**

Notes: SR = surface runoff; SC = sediment concentration; SL = soil loss; OM = organic matter; BD = bulk density; AS = aggregate stability.

soils showed intermediate SR and SL. SC was the highest in DU plots after 6 months (35.3 ± 1.88 g/L), and the lowest in HM soils after 9 months (45.6 ± 4.26 g/L) (Figure 2).

After 9 months from the treatments, TRS significantly ($p < 0.0001$) increased along the gradient HM < BP < DU, with values of 47.3 ± 6.66 s, 102 ± 3.51 s, and 123 ± 5.51 s, respectively.

3.2 Variability of soil properties after HM and BP treatments

Again, ANOVA showed that both soil condition and time (except their interaction for BD, $p = 0.165$) resulted in significant differences in the properties of soil ($p < 0.0001$) (Table 2). In more detail, OM and AS were generally higher in soils treated with BP and HM compared to the control plot, and these properties significantly increased over time. The highest values were measured in HM soils after 9 months (2.66 ± 0.02% for OM and 0.78 ± 0.02 for AS), while the lowest OM and AS were found in DU plots, again after 9 months (1.07 ± 0.02% and 0.21 ± 0.02, respectively).

BD was significantly lower and progressively decreasing (although non-significantly) under all soil conditions. DU and HM plots showed the maximum (1.55 ± 0.04 kg/m^3, after 3 months) and minimum (1.19 ± 0.01 kg/m^3, after 9 months) values, respectively (Figure 3).

All root characteristics of *Zoysia* grass grown in HM plots were significantly different ($p < 0.0001$) at the three dates, and increased over time. The maximum values of RB, RL and RWD were 29.1 ± 0.66 g, 24.6 ± 1.28 cm and 0.67 ± 0.02 kg/m^3, respectively (Table 3).

Table 3. Mean ± standard deviation (n = 3 replicates per plot) of root characteristics measured on hydromulched soils at three dates in the study area (Khortum forest, Guilan province, Iran). Different letters indicate significant differences after Tukey's test ($p < 0.05$).

Time (months)	Root biomass (g)	Root length (cm)	Root weight density (kg/m^3)
3	13.9 ± 0.53 a	10.7 ± 0.61 a	0.50 ± 0.02 a
6	20.7 ± 1.49 b	15.5 ± 0.61 b	0.59 ± 0.02 b
9	29.1 ± 0.66 c	24.6 ± 1.28 c	0.67 ± 0.02 c

3.3 Overall impacts of HM and BP treatments on soils through multivariate statistical analysis

The correlation analysis showed very high and always significant Pearson's coefficients (r) between all pairs of soil properties or hydrological variables. The maximum value of r (0.99) was calculated for the pair SL and SR. It is also worth noting the high correlations between the soil properties on one side, and the hydrological variables on the other side, with a minimum absolute r of 0.65 between SC and AS (Figure 4).

PCA identified a derivative variable (the first Principal Component, PC1), which alone explains more than 85% of the total variance in the original variables. The latter were associated to PC1 by very high loadings (absolute value > 0.800), positive for OM (0.967), AS (0.950) and SC (0.800), and negative for BD (–0.949), SR (–0.957) and SL (–0.940) (Figure 5).

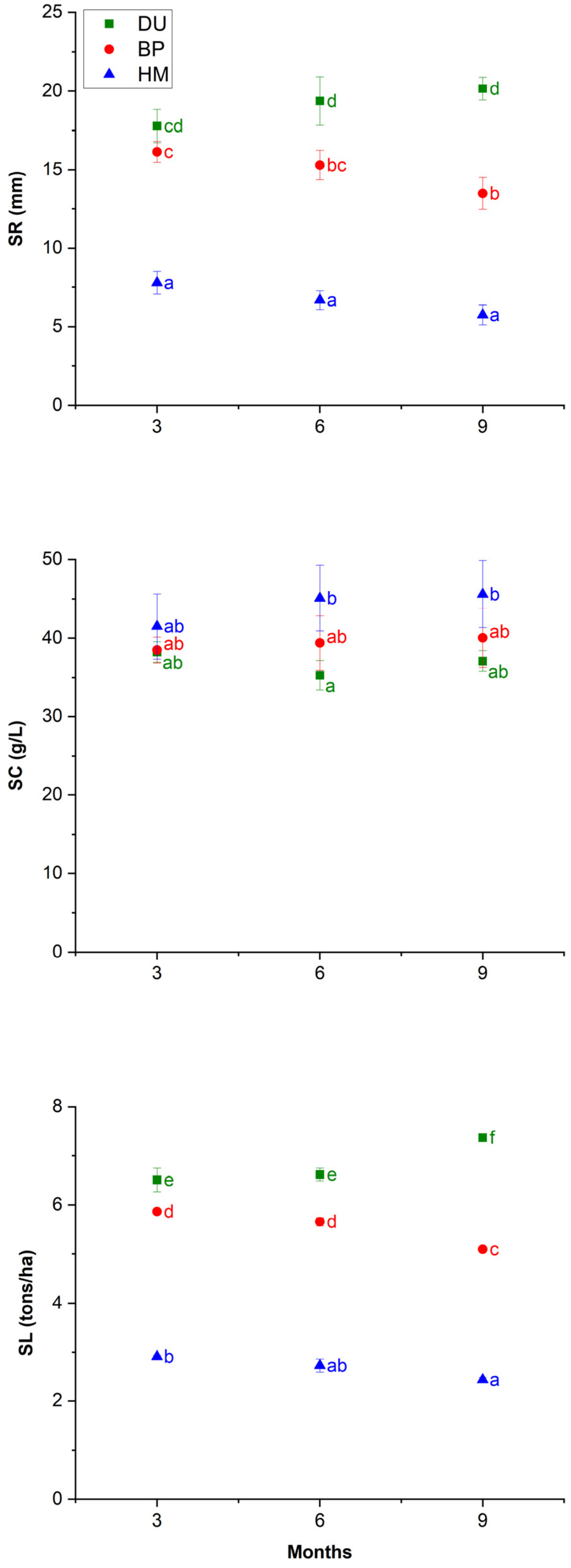


Fig. 2. Mean ± standard deviation (n = 3 replicates per plot) of surface runoff (SR), sediment concentration (SC) and soil loss (SL) under the three soil conditions (BP = treatment with bioplastics; DU = deforested and untreated soil; HM = hydromulching) and at three dates (3 = three months; 6 = six months; 9 = nine months) in the study area (Khortum forest, Guilan province, Iran). Different letters indicate significant differences after Tukey's test ($p < 0.05$).

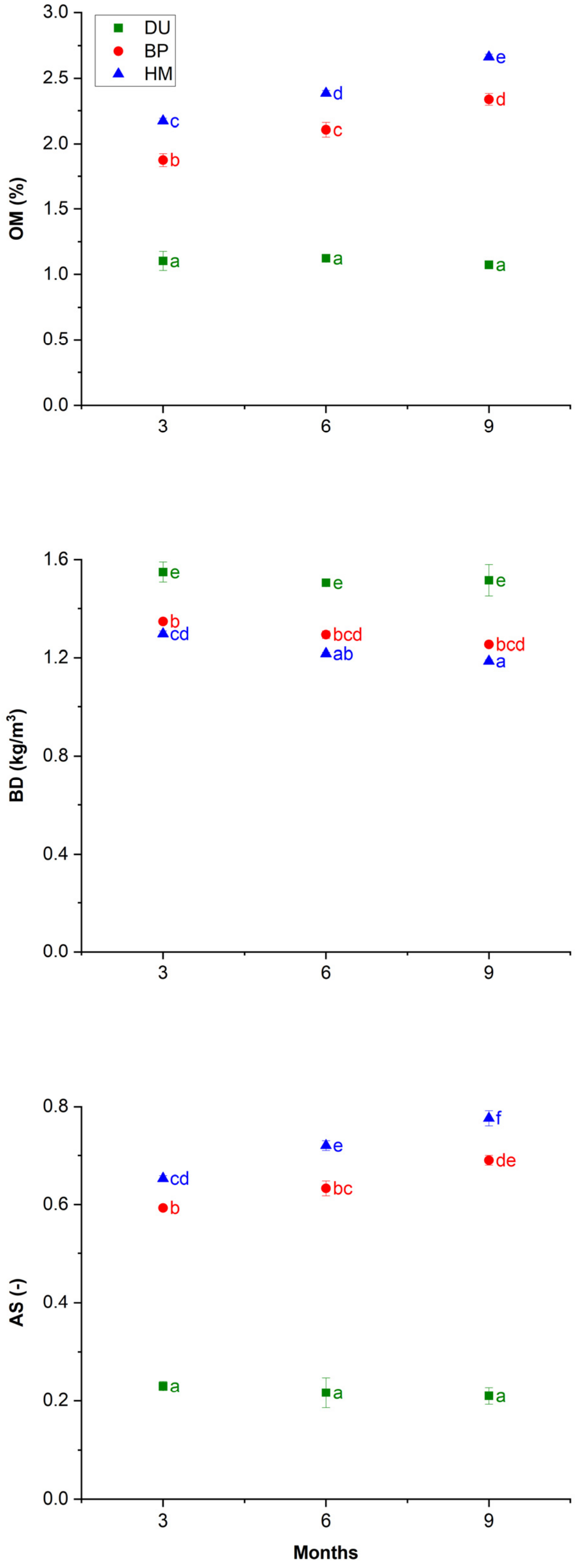


Fig. 3. Mean ± standard deviation (n = 3 replicates per plot) of organic matter (OM), aggregate stability (AS) and bulk density (BD) of soils sampled under the three soil conditions (BP = treatment with bioplastics; DU = deforested and untreated soil; HM = hydromulching) and at three dates (3 = three months; 6 = six months; 9 = nine months) in the study area (Khortum forest, Guilan province, Iran). Different letters indicate significant differences after Tukey's test ($p < 0.05$).

Fig. 4. Heatmap with Pearson's correlation coefficient (r) between pairs of soil properties and hydrological variables of samples collected under the three soil conditions (BP = treatment with bioplastics; DU = deforested and untreated soil; HM = hydromulching) and at three dates (3 = three months; 6 = six months; 9 = nine months) in the study area (Khortum forest, Guilan province, Iran). Notes: all values are significantly different from zero ($p < 0.05$); OM = organic matter; AS = aggregate stability; BD = bulk density; SR = surface runoff; SC = sediment concentration; SL = soil loss.

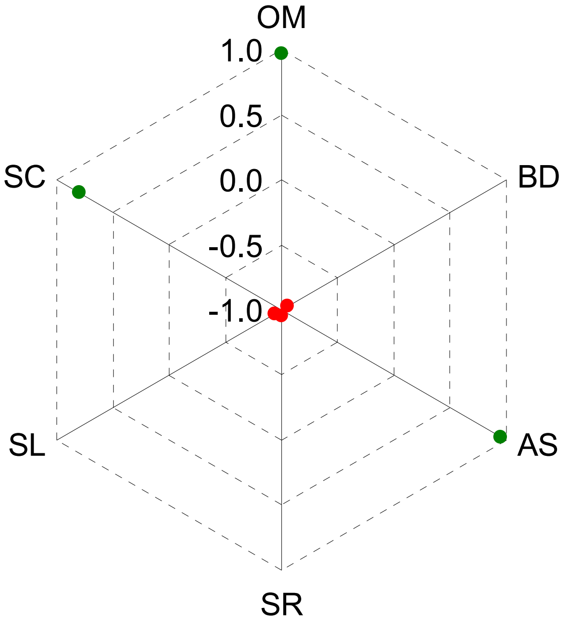


Fig. 5. Loading factors of original variables on the first derivative variable (PC1) calculated by Principal Component Analysis applied to samples collected under the three soil conditions (BP = treatment with bioplastics; DU = deforested and untreated soil; HM = hydromulching) and at three dates (3 = three months; 6 = six months; 9 = nine months) in the study area (Khortum forest, Guilan province, Iran). Notes: SR = surface runoff; SC = sediment concentration; SL = soil loss; OM = organic matter; AS = aggregate stability; BD = bulk density; positive and negative loadings are in green and red, respectively.

BP (except for the observations of soil properties and hydrological variables after 3 months) and HM soils showed positive values of PC1, while the scores of DU plots on the first PC1 were negative (Figure 6).

AHCA grouped the observations of soil properties and hydrological variables in three clusters: a first cluster consisted of all BP s and values of DU plots after 3 months, the second cluster was composed by all DU observations, and the third cluster grouped all the HM soils (Figure 7).

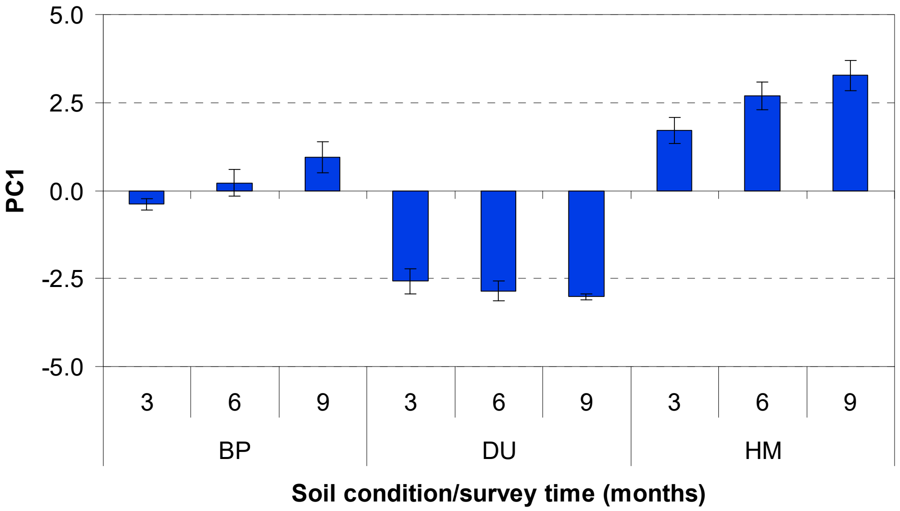
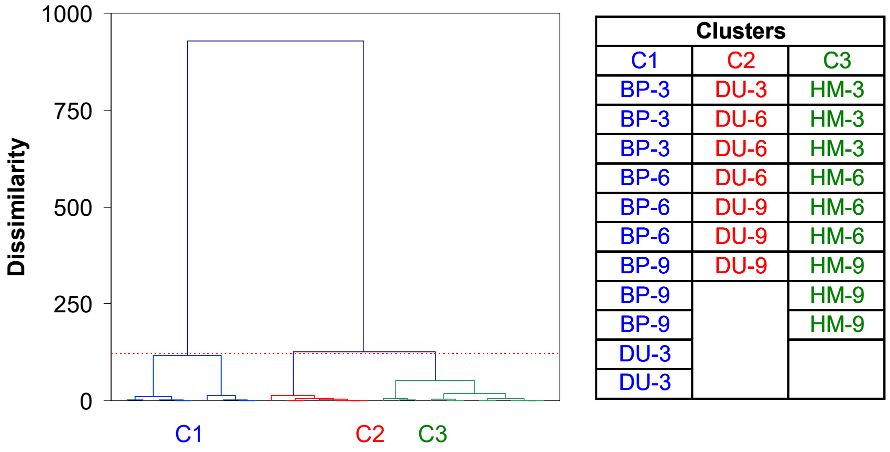


Fig. 6. Scores (mean ± standard deviation, n = 3 replicates per plot) of properties of soil samples and hydrological variables on the first derivative variable (PC1) calculated by Principal Component Analysis applied to samples collected under the three soil conditions (BP = treatment with bioplastics; DU = deforested and untreated soil; HM = hydromulching) and at three dates (3 = three months; 6 = six months; 9 = nine months) in the study area (Khortum forest, Guilan province, Iran).



Clusters		
C1	C2	C3
BP-3	DU-3	HM-3
BP-3	DU-6	HM-3
BP-3	DU-6	HM-3
BP-6	DU-6	HM-6
BP-6	DU-9	HM-6
BP-6	DU-9	HM-6
BP-9	DU-9	HM-9
BP-9		HM-9
BP-9		HM-9
DU-3		
DU-3		

Fig. 7. Dendrogram of the original variables (properties of soil samples and hydrological variables) (left) and cluster (C1, C2 and C3) composition provided by the Agglomerative Hierarchical Cluster Analysis (right) applied to soil samples collected under the three soil conditions (BP = treatment with bioplastics; DU = deforested and untreated soil; HM = hydromulching) and at three dates (3 = three months; 6 = six months; 9 = nine months) in the study area (Khortum forest, Guilan province, Iran). Legend: the y-axis of the dendrogram reports the similarity level, while the red dotted line the clustering level; the number after the dash in the table is the survey month of the sample under the reported soil condition.

3.4 Modeling the hydrological and erosive response of soil after HM and BP treatments

The predictions of SR and SL using linear regressions were given by the following equations:

$$\text{SR (mm)} = 28.043 - 8.508 \times \text{OM (\%)} + 5.689 \times \text{Soil condition(BP)} + 1.247 \times \text{Soil condition(DU)} - 1.839 \times \text{Time(3 months)} - 0.651 \times \text{Time(6 months)} \quad (1)$$

$$\text{SL (tons/ha)} = 9.123 - 2.534 \times \text{OM (\%)} + 2.088 \times \text{Soil condition(BP)} + 0.827 \times \text{Soil condition(DU)} - 0.648 \times \text{Time(3 months)} - 0.354 \times \text{Time(6 months)} \quad (2)$$

Both equations use one quantitative (OM) and two categorical (Soil condition and time) variables. Adding further quantitative variables (AS and BD) did not increase the models' prediction capacity.

These simple models showed an excellent prediction accuracy of both SR and SL, shown by the very high goodness-of-fit between observations and predictions (Figure 8) and demonstrated by the very high coefficients of regression and Nash and Sutcliffe (both equal to 0.98 and 0.99, respectively). The highest errors between the observations and the corresponding predictions were 16.8% for SR and 6.89% for SL. No multicollinearity in the data was found, as shown by the calculated Variable Inflation Factor (VIF) among pairs of variables. In this regard, for both equations the highest VIF was equal to 8.18, below the limit of possible data multicollinearity (VIF = 10) stated by Marquardt (1980).

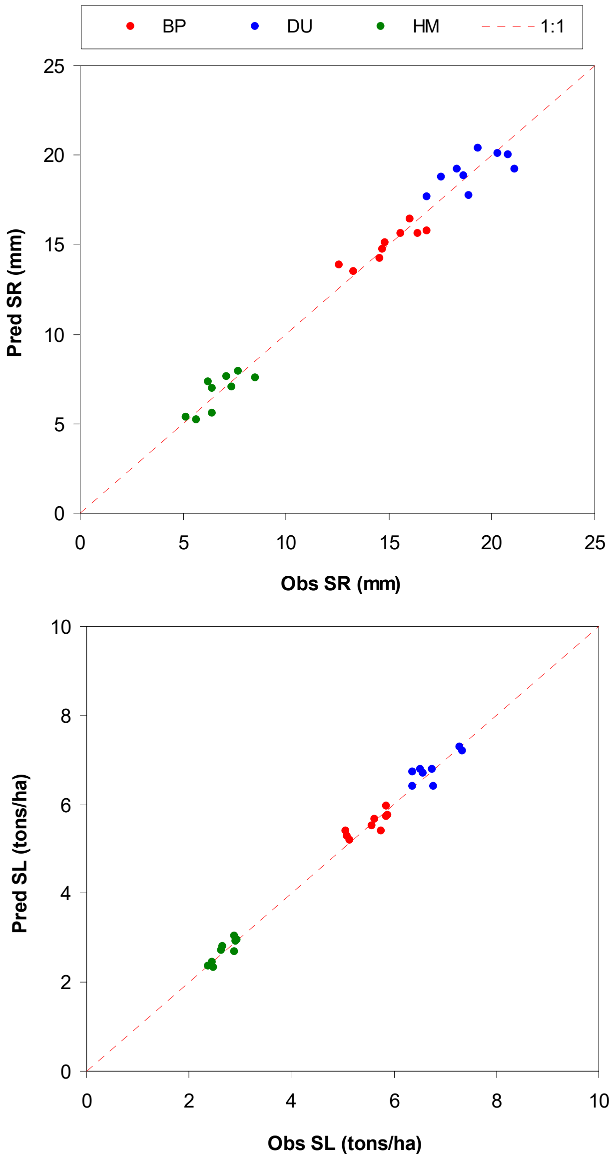


Fig. 8. Scatterplots of surface runoff (SR) and soil loss (SL) observed under the three soil conditions (BP = treatment with bioplastics; DU = deforested and untreated soil; HM = hydromulching) and at three dates (3 = three months; 6 = six months; 9 = nine months) and predicted using linear regression equations in the study area (Khortum forest, Guilan province, Iran).

4 DISCUSSIONS

4.1 Hydrological and erosive response of soil after HM and BP treatments

Under the experimental soil conditions, the measured SL was extremely high (up to 6–7 tons/ha), and this proves that erosion is a severe concern for soil conservation in the studied area. It is true that the simulated rainfall had a very high intensity (approx. 100 mm/h), but one must bear in mind that the soil loss was produced by only one event. This means that erosion following only one but extreme rainstorm in the studied area is close to the tolerance limit for croplands (about 10–12 tons/ha-year) at the annual scale (Bazzoffi, 2009; Wischmeier, 1978). Therefore, in the case of very wet years, a sequence of 2–3 rainstorms with high intensity may result in a cumulative soil loss far exceeding this tolerance limit. This erosion rate is even more alarming, since soil loss is not generated on steep hillslopes (in this case study, approx. 15%), where soil detachment may be higher by more than 50% compared to lower slopes (Lucas-Borja et al., 2022). A careful control of these soil losses in the area is thus essential, to avoid severe on-site and off-site effects.

Both treatments reduced SR and SL, but their effectiveness was higher for HM and lower for BP. In more detail, while the reductions in both variables were close to 20% in the soils treated with BP, HM reduced SR and SL by over 60%. The soil erodibility estimated for the HM plots is much higher compared to the values measured in grasslands in the same environment (Parhizkar et al., 2020a). That increase was explained by the disturbance effects of the severe wildfire on the deforested soils. Also Zhang (2003) stated that disturbed soils can be more easily detached compared to control sites, due to the destruction of soil structure.

The reduction in SL was ascribed to changes in SR rather than to variations in SC, since, in the treated soils, the latter variable decreased by less than 20%. This important role of SR in the overall erosion is further demonstrated by the very high coefficient of correlation (r = 0.99) between SR and SL, as shown by Pearson's correlation matrix. It worth mentioning that the time elapsed after the treatments played a much minor role in soil's hydrological and erosive response, since the differences in SR and SL throughout the monitoring period were generally non-significant. Exceptions are the significant variations in SR for BP and DU plots after 3 and 9 months, respectively, and in SL for HM soils between the same dates. The latter exception is important, since it proves that the effectiveness of hydromulching against soil erosion increases over time. Past studies have shown that hydromulching can noticeably reduce erosion in several environments (e.g., Hubbert et al., 2012; Parsakhoo et al., 2018a; Prats et al., 2013; Ricks et al., 2020). This beneficial effect against soil degradation issues is somewhat expected, since the mulch application is generally effective at restoring the vegetation cover thanks to a dense root system of grass in the short term (Robichaud et al., 2000). However, the increase in soil resistance to erosion in hydromulched soils due to the effects of roots becomes significant after no less than 6 months, as shown by the paired analysis of root characteristics and soil loss.

Not only the SR was lower after HM and BP treatments, but also its starting time (TRS) was longer (for both soil conditions about two-fold the value measured for DU soils). In other words, the treatments delay the runoff generation compared to the control. This means that the flooding risk in treated soils is noticeably reduced in both magnitude and time. This delay effect is also reported by other authors (e.g., de Lima et al., 2019; Keesstra et al., 2019; Yanosek et al., 2006), who observed that mulching is also effective in delaying the runoff initiation.

The reasons for the reduction in the hydrological and erosive response of soil after the treatments may be diverse. Both the mulch cover thanks to HM application and the presence of BP residues over ground increased the soil capacity to: (i) absorb rainwater, which reduces the share of precipitation that turns to runoff, and, therefore, the soil particle detachment due to overland flow; (ii) slowdown surface water, which reduces the water velocity and therefore its drag force on soil particles; and (iii) protect the soil surface against raindrop impact, which lowers the erosivity of precipitation. These beneficial effects of the experimented soil conservation techniques on soil hydrology support other ecological advantages, such as the increase in water capacity retention and infiltration (Prosdocimi et al., 2016), which, however, were not focused by this study.

4.2 Variability of soil properties after HM and BP treatments

In addition to the improvements in soil hydrology, the decrease in runoff and erosion rates due to the treatments may be essentially ascribed to the beneficial changes in key soil properties. The analysis of soil properties shows that both HM and BP (the latter by a slightly lower extent) improved the main physical properties of soil (e.g., increases in AS by about 200%) compared to the control plots, which could be explained by the higher content in OM (on average +100%). This effect is more pronounced in HM soils, thanks to the presence of grass roots in the treated plots, which increase OM and AS more than in the BP soils (in which OM only derives from starch decomposition). It is well known that soil detachment is noticeably influenced by the effects of plant root characteristics (De Baets and Poesen, 2010; Gyssels et al., 2006; Mamo and Bubenzer, 2001a, 2001b). This study is in close agreement with this statement, since it has demonstrated that grass roots noticeably reduce soil erodibility in HM soils compared to BP application. Also other studies found that soil resistance to erosion is closely associated to plant root characteristics (e.g., Li et al., 1992; Wang and Zhang, 2017; Wang et al., 2015). For instance, Zhang et al. (2013) even stated that soil detachment capacity exponentially decreases when root weight density increases. Moreover, Parhizkar et al. (2020a) reported the beneficial effects of vegetation roots on the reduction in soil detachment in forestlands and woodlands affected by intense rill erosion. In this study, these beneficial effects are noticeably variable throughout the monitoring period, and thus a further reduction in SR and SL may be expected over time.

The noticeable increase in soil OM in the treated soils is in line with the expectations, since other studies have demonstrated that the addition of organic residues to soil significantly increases the its organic carbon pool (Dume et al., 2016; Luna et al., 2018; Sánchez-Monedero et al., 2008). High OM is beneficial for the stability of soil aggregates (Zeraatpisheh et al., 2021), since the organic compounds bind soil particles as a natural cement, and for the reduction in soil compaction, thanks to swelling resulting from the higher macroporosity (Kutílek, 2004; Hillel, 1998). All these effects lead to high resistance of soil to particle detachment due to the overland flow and rainsplash erosion. According to Caravaca et al. (2004) and Khormali et al. (2009), an improvement in soil structure (due to increased AS and decreased BD) noticeably reduces soil detachment (Knapen et al., 2007; Li et al., 2015). Moreover, the detected changes in soil AS and BD resulting from OM effects in the treated soils agree with the results of several studies (e.g., Lemenih et al., 2005; Shepherd et al., 2001; Wang et al., 2018a). These studies have highlighted the strong associations between soil organic matter on one side, and aggregate stability indices (Shepherd et al., 2001) and bulk density (Lemenih et al., 2005) on the other side.

4.3 Overall impacts of HM and BP treatments on soils through multivariate statistical analysis

The correlation analysis showed close associations among all analysed variables, and the first PC provided by PCA itself can be considered as a synthetic measure of the changes in hydrological variables and properties of soil due to the treatments. In other words, PC1 increases with OM and BD, and decreases when BD, SR, SC and SL increase. Moreover, positive values of PC1 are associated to an improved hydrological response of soil compared to the control, as detected for plots treated with BP or HM.

The aforementioned significant variations in both hydrological variables and properties clearly discriminate the three soil conditions (DU, HM and BP), as evidenced by the AHCA, which identified as many distinct clusters grouping the observations. This discrimination demonstrates on a multivariate statistical approach that treated and untreated soils are clearly different in terms of hydrological response and physical properties. This is due to the higher contents of OM and stability of aggregates in soil as well as to lower compaction of the treated soils as well as to its increased resistance to particle detachment. In the case of hydromulched soils, this discrimination is enhanced by the presence of plant roots, helping to further decrease soil bulk density due to the creation of a system of continuous pores (Dunkerley, 2000; Gyssels et al., 2006; Shinohara et al., 2016) and to increase aggregate stability due to the stabilising action of roots (Sun et al., 2022; Wang et al., 2018b).

4.4 Modeling the hydrological and erosive response of soil after HM and BP treatments

The multiple-regression models proposed in this study has indicated that both SR and SL can be predicted with very high accuracy using simple but powerful equations with a linear mathematical form. These models are of easy applicability, using only one simply measurable variable (OM content of soil) and two categorical variables, related to soil condition and time elapsed from the treatment, which do not require any measurements to estimate runoff and erosion with an excellent reliability.

Undoubtedly, this modelling exercise may be considered as a "black-box" approach (Nearing et al., 1991), which is however adopted in many environmental studies. Often the hydrological processes are very complex, and the input data for modelling are low. These process complexity and data scarcity make the use of physically-based models to simulate soil erosion very difficult. In this case, simple or multiple regression models with different analytical structure can be a viable alternative (Parhizkar et al., 2021b).

4.5 Limitations and perspectives

These results are promising in view of validating viable soil conservation practices against the hydrogelogical hazards in degraded forests at least under the experimental conditions. However, further research is needed for their validations for broader applications, due to some limitations of this study. For instance, upscaling from plot to the hillslope scale is adviced, considering that rainfall simulations in smaller plots can overestimate runoff and erosion compared to the hillslope-scale experiments (Prats et al., 2017). Soil's hydrological response should also be monitored under natural precipitation, in order to take into account the variability of the weather input.

About the modeling approach to runoff and erosion prediction in this study, it is worth highlighting that the developed multiple-regression models are specific for the rainfall variables (depth and intensity) used for the simulations. Therefore, for a larger applicability of these prediction models, specific equations must be developed for different rainfall characteristics. For instance, intensity-duration-frequency curves, which estimate rainfall depth and intensity at a given return interval, must be used to calibrate the values of the regression coefficients of the proposed models. Unfortunately, the application of regression models out of the context where they have been validated needs for specific calibration activities with a case-by-case setup of their coefficients (Nearing et al., 1991). However, the hydrological models that are simple and require few and easy-to-collect input parameters are very useful for those modellers that only need rough estimations of soil erosion in similar environments as those of the calibration sites.

5 CONCLUSIONS

The comparison of hydromulching and application of bioplastics on soils affected by intense deforestation and burning under a high-intensity rainfall simulated at the plot scale has shown that: (i) both treatments reduce the high surface runoff and soil loss measured in the untreated soils, but this reduction is higher in hydromulched soils compared to the plot treated with bioplastics, thanks to the beneficial effects of grass roots; (ii) the improvement in soil's hydrological and erosive response due to the treatments may be essentially ascribed to the changes in the physical properties, such as the increases in organic matter and aggregate stability, and reduction in bulk density of soil, mainly due to the grass root action; (iii) according to the multivariate statistics, the three soil conditions (hydromulching, application of bioplastics and lack of treatment) are noticeably different each to other, and the first Principal Component of PCA can be considered a synthetic measure of the beneficial effects of the treatments; and (iv) the two proposed multiple-regression models can predict surface runoff and soil loss with very high accuracy for a precipitation with given depth and intensity.

Overall, the study has suggested to land managers the prioritization of hydromulching over the application of bioplastics as a more effective soil conservation technique as well as to hydrologists two linear models that can predict surface runoff and soil loss with very high accuracy for a precipitation with given depth and intensity. Further research is, however, needed to validate the experimented soil conservation techniques in the same environment (e.g., through upscaling from plot to the hillslope scale or experiments under natural precipitation) as well as in other experimental conditions (different climate and soil types). Moreover, although being easy to be applied and require few input data, the proposed prediction models require targeted calibration of the values of the regression coefficients in the same or in different environmental conditions.

Funding. Faculty of Agricultural Sciences, University of Guilan.

Acknowledgements. The authors thank the Faculty of Agricultural Sciences, University of Guilan for their support and experimental assistance.

Data availability. The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of interest. The authors declare no conflict of interest.

Author contribution statement.

- Misagh Parhizkar: Conceptualization, Formal analysis, Data Curation.
- Manuel Esteban Lucas-Borja: Formal analysis, Writing - Review & Editing.
- Pietro Denisi: Formal analysis, Writing - Review & Editing.
- Nobuaki Tanaka: Formal analysis, Writing - Review & Editing.
- Demetrio Antonio Zema: Formal analysis, Writing - Original Draft, Writing - Review & Editing.

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Received 27 July 2024
Accepted 23 October 2024